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Review of supporting scheme for island powersystem storage

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ABSTRACT

This paper proposes a support mechanism for energy storage devices for island power systems where intermittent renewable generation is rapidly growing. We base our proposal on the maturity level of storage devices (Chen et al., 2009 [7]) and on the linear model for the development of innovations [14]. We focus on storage technologies that can be technically developed in island power systems and that achieve the technical needs of these systems. We conclude and recommend the adoption of a feed-in tariff with a price varying with the time of day to push for the deployment of power storage avoiding the curtailment of massive intermittent renewable generation.

Contents

1. Introduction

The integration of massive photovoltaic and wind power into island power systems in Europe is confronted by a number of problems. These systems can only accommodate a very limited capacity of Renewable Energy Sources (RES) power. Indeed, beyond a certain amount of intermittent renewable power, it is not possible to cut some conventional thermal plants to balance generation and load because these conventional thermal power plants are used to provide the necessary reserve margin to balance the power system instantaneously [5]. This technical constraint can reach different levels according to the size and the maturity of the island system. In the example of Reunion Island, the limit is 30% of intermittent RES that can be integrated in the system. When the 30% limit is reached, the system operators will cut intermittent RES production surplus to maintain the balance between generation and load. This technical constraint limits the integration of more renewable energy in island power systems and makes it more difficult to achieve objectives of energy independence and reduction of Greenhouse Gas (GHG) emissions. There are several technologies already available to overcome the constraints of integrating large amounts

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of RES. Among the most traditional ones, it is possible to develop highly flexible conventional thermal power plants such as small oil-fired power stations. But these plants have two major drawbacks. First, their use makes the power system more dependent on external resources that are already difficult for the isolated island systems to obtain at a low price. Second, if the integration of more intermittent RES entails the parallel insertion of flexible thermal power plants, the net CO_2 balance could be negative for the island systems. Another solution that we study here is to rely on electricity storage.[1]

Storage facilities have multiple positive impacts on the electricity systems. First, electricity storage logically makes it possible to insert more intermittent RES while participating in the global balance between generation and load in a more predictable way. Second, storage can flatten the load curve of the system. The renewable or baseload power plants are then more called on to fill in the storage facilities during low consumption periods. And during periods of high consumption, the stored energy is returned to the system, thereby reducing the need for peakload power plants that relatively emit more CO_2 than renewable or baseload ones. If pumped hydro storage technologies are already known to be profitable for island power systems in limited situations [6,34], other storage technologies adapted to massive deployment on islands are still in the early stages of industrial development despite their potential attractiveness.

As highlighted by He and Zachmann [20], the literature about electricity storage in the power market has mainly focused on the calculation of the arbitrage value of energy bought at a low price and stored and subsequently sold at a higher price. This exercise has been done in several markets (PJM and New York in the USA by Walawalkar and Apt [39] and by Sioshansi et al. [37], Nordpool by Lund et al. [25], Spain by Dufo-Lopez et al. [11]). And several assumptions have been used for the operation of the storage facility (fixed period of arbitrage for Walawalkar and Apt [39], optimization of the storage facility over two weeks by Sioshansi et al. [37], over one year by Lund et al. [25], use of the real option theory by Muche [29]). He and Zachmann [20] open the research field and determine the return on invested capital of different technologies for different markets, comparing the arbitrage value with the fixed cost of different storage technologies considering their different power ratings. They conclude that for three representative markets in Europe (France, the Netherlands and Scandinavia), no storage facility is profitable despite the benefits they bring to these power systems. Sioshansi [36] sums up the diversified services that storage can bring to power systems and highlights the inconsistencies in current market designs, which prevent a market-based development of storage. One important reason for this is the lack of suitable mechanisms allowing the investor to capture the overall value of storage by providing multiple services to the power system. The efforts to aggregate several revenue streams often come up against regulatory frameworks which forbid the exchange of information between the regulated and deregulated actors. Sioshansi [36] helps us to understand that the combination of services could lead to a better perspective for the development of storage. Following this line, He et al. [19] develop an initial reflection on a business model that takes account of this problem in power systems. The core idea of their model lies in organizing an auction chain in which the right to use available storage capacities is auctioned among different actors. To sum up, the integration of storage in the power system is faced with threefold market failures. 1° Storage can help the development of intermittent RES and reduces CO_2 emissions from other power plants but the pricing of CO_2 still does not make it possible to internalize this positive externality and to overcome the investment and management cost of storage. 2° The scientific and technological efforts associated with RD&D and demonstration pilots have a public good character and need suitable treatment to be overcome. 3° Innovations in the power system (such as storage) face technological entry barriers due to the pre-existence of mature solutions (such as oil-fired power plants) that can provide a similar service at, currently, a lower cost. Its learning curve is then limited.

The existence of these three market failures then leads us to wonder what suitable form of public support and regulatory framework would be required for the development and deployment of storage technologies in island power systems.[2] In order to answer this question, we will rely on the work by Foxon et al. [14] to associate the adequate support mechanism to technologies depending on their maturity. In particular, this was done previously for renewable generation technologies [12,13]. We will also rely on the work by Chen et al. [7] to characterize the maturity of the different storage technologies. What is more, in order to minimize the reliance on support mechanisms while maximizing the possibility of developing storage technology, we will also consider three characteristics of storage devices when designing support mechanisms for storage technologies. The first characteristic is the optimal use of storage. The public support mechanism should take account of the fact that the efficiency of energy storage for the power system as a whole depends on the specific times of the day when it withdraws and injects energy and on the location of storage devices. The second characteristic that distinguishes the different storage technologies is the set of services they can provide to the power system (power quality–voltage variation, voltage and current transient, harmonic content in waveforms–balancing, at least daily storage duration, location flexibility). Some storage technologies may be able to provide some services to the system while others may not (for instance, balancing). The public support for storage shall take account of the differences between technologies in terms of ability and maturity of service they can provide and the revenue generated from selling these services. The last characteristic is the degree of centralization of storage facilities. Different management schemes could be applied to storage according to the degree of centralization. Consequently support mechanisms shall apply differently depending on the degree of centralization and on the kind of actor responsible for managing storage (fully independent, integrated with production, or possibly with the Transmission System Operator–TSO). Finally, the value for these three characteristics of storage (1) its double function of storing and removing energy, (2) the other services it can provide and (3) its degree of centralization and location on the network) will be all the higher (without support) when the market design is efficient and storage is exposed to market signals. A smaller reliance on support mechanism will then be needed (as shown by [22] in the case of wind power).

The paper is organized as follow. First we identify the services that storage could provide to island power systems to facilitate the integration of intermittent RES. We then establish the electrochemical storage technologies that can deliver these services. Second, we recall the various forms of public support for the development of clean technologies in the electrical system. We can then link the various stages of the technological and industrial development of new technologies with the adequate support instruments. In the last section, we will also recommend the form of adequate support for these technologies given their technical

[1] When possible, another solution that offers greater flexibility is to connect islands together (e.g. the Canary islands) or to connect them to the continental system (e.g. the main Balearic islands connected to the Spanish network).

[2] Note that internalizing the market failures for storage may also benefit consumers by allowing lower prices at peak times [36].

and economic maturity and their association with the development of intermittent renewable generation for different market designs. In particular, we will consider the perfect market design established by Hiroux and Saguan [22] and the market design of the French island power systems.

2. Energy storage and renewable energy

Energy storage helps to compensate the technical effects of intermittent generation on the operation of a power system. In order to assess the benefits of energy storage, we can look at the impact of intermittent renewable generation on the different modules of tasks that comprise the electricity system. First we will consider there is no storage and after we will introduce storage.

2.1. Specific problems with island power systems

According to Perez and Ramos Real [30] and Weisser [41,42], island systems have specific economic and technical characteristics due to the insular nature of the small electrical supply networks. Other things being equal, island power systems are more tightly dimensioned than large ones because energy is far more expensive in these markets. Island power systems are therefore less able to respond to, or to absorb, shocks and risks. Each element constituting such small networks is consequently very significant for the entire grid. The loss of a group or the loss of a single element of the network then has a much greater impact than in a larger network. Insularity makes these small systems more difficult to manage than large interconnected systems for four reasons.

First, the main problem is that electricity supply in these territories is more expensive because they face high fuel transport costs. These systems generally run on fossil fuels imported at a high price.[3]

The second problem encountered by small electricity systems is that the network faces a lot of voltage constraints. This is because the small size of the network means that voltage drops have a significant effect on the whole network compared to the management of larger system.

The third problem is that the island networks do not benefit from the immediate solidarity offered by the number effect of producers connected together on the large continental network. The very short run adjustment between “power and frequency” is thus more difficult to achieve. Isolation makes it necessary to maintain more reserve capacity to ensure adequate supply. They cannot therefore benefit from the great stability of large, interconnected electricity systems.

The last problem is that the above-mentioned constraints require planning and management procedures that do not benefit from a major learning effect like the one experienced by mainland territories. Even worse, it is very hard to define transparent management rules or even clear safety rules for island power systems because each network is extremely specific (depending on its geographical size, number of inhabitants, economic activities, weather conditions, etc.). The comparison of the on-going safety requirements of some isolated electric systems reveals considerable diversity (Table 1).

The island power systems are then difficult to manage and delicate to operate. This makes them very sensitive to any disturbances and the introduction of any innovation should aim at increasing their stability and their resistance to shocks.

2.2. Impact of intermittent RES and the need for energy storage

It is advisable to stress that the introduction, on insular networks, of massive intermittent renewable energy sources notably photovoltaic and wind energy is not an easy matter because it makes it more difficult to manage these fragile networks. In the absence of suitable storage devices or additional flexible thermal generation units,[4] the integration of intermittent renewable energy has four major impacts on the electrical system.

First, having priority on the network, the introduction of massive amounts of wind and photovoltaic energy modifies the way the system is operated as a whole. The conventional producers must adapt their production curve to the real-time fluctuations of wind and photovoltaic production. They are dispatched after this priority energy. The resulting modification of the merit order induces additional costs because some power stations previously being dispatched will now be dispatched under a more stressed pattern of use, operating with a lot of variations and/or at suboptimal levels compared to their technical design.

Second, the introduction of intermittent renewable energy increases the need for real-time balancing and reserve capacity to maintain frequency close to 50 Hz. This is due to the stochastic variations and the low predictability of these energies vis-à-vis the operational horizons of power system from seconds ahead to a day ahead [21]. For example, in one hour, Reunion island may lose no more (but still) 45% of its photovoltaic production [3]. What is more, these power sources are non-dispatchable because their energy must necessarily be used at the time of production or, otherwise, be lost. If account is taken of these characteristics, wind and photovoltaic technologies cannot be mobilized for power and frequency adjustments under current security rules.

Third, beyond a certain volume of intermittent generation, it may sometimes be necessary to disconnect a share of this production to ensure the balance between generation and load, or to manage network congestion [5].

Finally, the inclusion of intermittent generation reduces the quality of the power signal (with the presence of harmonics and variations in the voltage amplitude). This is due to the stochastic variations of these energy sources and to the technology used to produce electricity from these sources.

The low flexibility of base-load thermal power units does not allow for sufficient change in their production level to balance generation and load in a reliable way with a massive amount of intermittent generation. The instantaneous mismatch between production and consumption is well known for wind generation [28]. It is also true for PV production, although to a lesser extent. This is illustrated in Fig. 1, which shows that PV production (represented by the sum of the following areas: the yellow area, the shaded green and yellow one and the shaded red and yellow one) consistently exceeds consumption (red line) during the daytime while it is absent during the evening peak.

Another important constraint to consider is that the grid has a limited capacity. This is all the more true considering that intermittent renewable generation in island power system is generally concentrated in a limited number of geographical areas. For instance, PV production is concentrated in Reunion Island in the North and South of the island, where the resource is most abundant. The wind farms will similarly be concentrated under the prevailing winds: for instance, the South East of Reunion Island (see Fig. 2). It may then be necessary to limit the installed capacity of intermittent renewable generation

[3] This is because the required quantity is generally small and not frequently delivered. For more details on this point, see Ramos-Real et al. [35].

[4] Some possible scenarios of developing jointly gas and RES have being studied in Marrero & Ramos-Real, [27].

Table 1
Comparison of security rules for Islands.

	Installed capacity (MW)	Peak demand (MW)	Rules for primary reserve
Cyprus	990	775	10% of total load[a]
Crete	704	471	The largest group or all the wind production presents at time T[b]
Mallorca–Menorca	1098	914	
Ibiza Formentera	197	169	
Lanzarote-Fuerteventura	346	212	50% of the largest connected group[c]
Gran Canaria	860	552	
Tenerife	775	540	

[a] Petoussis and Stavrinos [33].
[b] Thalassinakis and Papoutsakis [38].
[c] Résolución de 28 de Abril de 2006, de la Secretaría General de Energía, por la que se aprueba un conjunto de procedimientos de carácter técnico e instrumental necesarios para realizar la adecuada gestión técnica de los sistemas eléctricas insulares y extrapeninsulares.

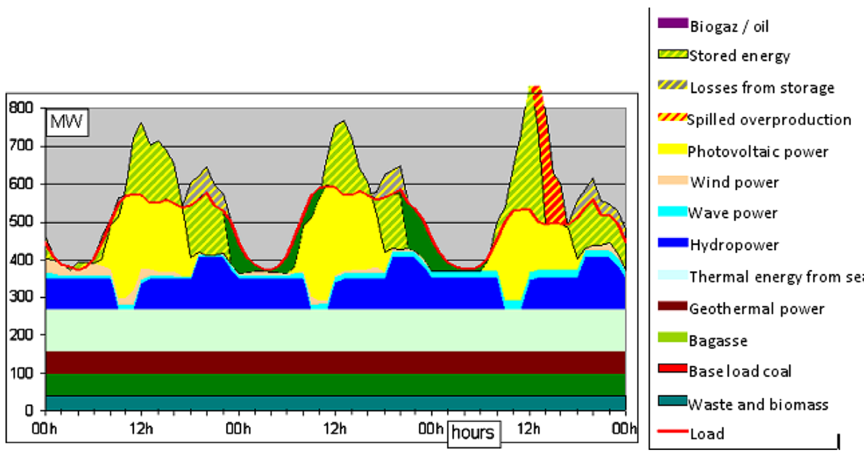

Fig. 1. Example of power generation for 3 days in Reunion Island for 2050 with spilled photovoltaic production. Adapted from ARER [3]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

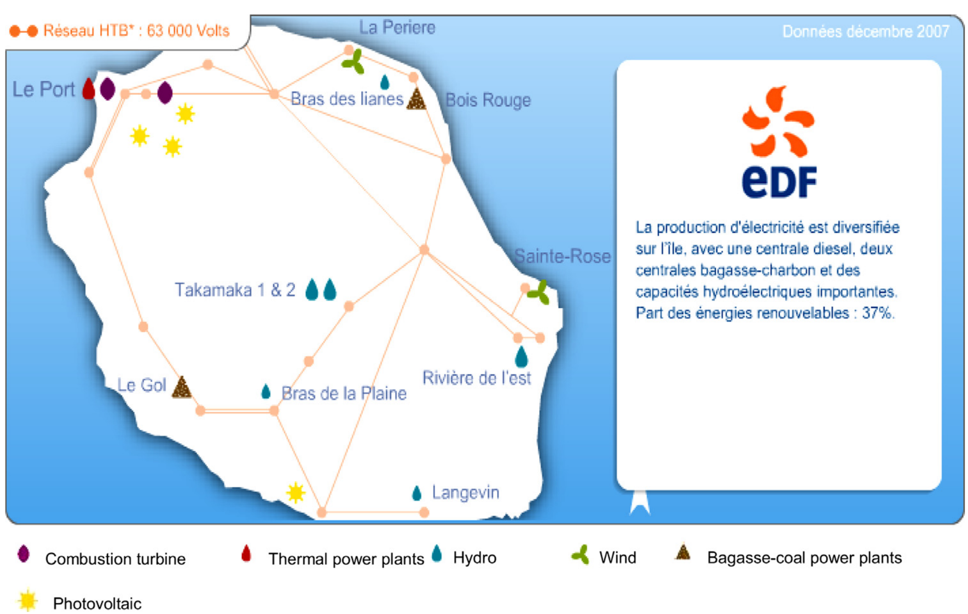

Fig. 2. Power network of Reunion Island. The installed photovoltaic capacity was 1.3 MW in the South and 1.75 MW in the North in 2007. Adapted from sei.edf.fr.

units because of network constraints. This limitation is reached efficiently only when it is required to spill a certain volume of those energy sources. Indeed, by increasing the installed capacity of these generation units, the volume of spilled energy naturally increases but the rest of the produced energy also increases. It may also be efficient to upgrade the network development to the capacity when the cost of any increase is larger than the value of increased RES production.

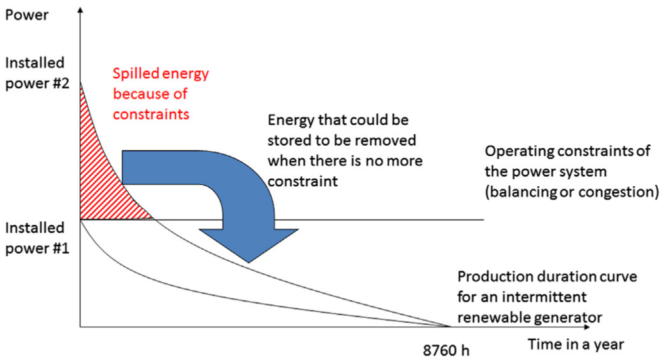

Fig. 3. Illustration of the impact of storage on the operation of intermittent generator in the presence of operating constraints.

Of course, the introduction and development of renewable energies could be a valid and robust instrument to make island power systems less dependent on foreign fossil fuels, more environmental friendly, and able to produce their energy in a more cost-effective manner. However, its interruptible and stochastic nature, together with isolation, will make their introduction on a massive scale rather difficult to manage, unless solutions such as storage are deployed.

Some storage technologies make it possible to offset significantly the above-mentioned effects of intermittent RES in island power systems. Some of them also create positive effects for the whole power system with four specific types of benefits.

First, the power electronics tools required for the integration of electrochemical batteries can also control and improve the quality of the power signal despite the stochastic variations of intermittent production.

Second, some storage technologies exhibit temporal dynamics that allow them to participate actively in balancing generation and load, either by providing power reserves or balancing.

Third, some technologies provide storage capacities in line with the needs of certain island power systems. For instance, in Reunion Island, the need for storing intermittent energy is primarily a daily storage requirement [3]. The presence of storage required for the integration of more intermittent renewable generation once installed can also help to flatten the load curve and thereby reduce the need to run peak load generation units that generate significant CO_2 emissions.

Last, a storage device can flatten the production duration curve of intermittent generators. This can limit the amount of spilled renewable energy otherwise needed to avoid congestion on the network where the generator is connected (see Fig. 3). Put simply, the storage device can be positioned close to either the producers, the consumers or in the center of the power grid. The closer the storage devices are to the sources of disturbances, the less these disturbances will interfere with the operation of the system overall. Moreover, locating storage devices in the center of the grid has the disadvantage of generating significant transit flows on the network while other locations can smooth the network usage. It is interesting to abound local intermittent sources to limit the use of storage and to play on the economies of scale for electrochemical technologies. The positioning of storage close to the intermittent generation is still the most appropriate one for the island power system [9]. Medium-sized, decentralized storage technologies are more suited to this need.[5]

2.3. Resolving the problems associated with intermittent energy thanks to the different storage technologies

Chen et al., 2009 [7] propose a technical and economic analysis of all energy storage technologies. We have used this analysis to assess the storage devices best suited to meeting the challenges raised by intermittent energy generation in island power systems. Chen et al., 2009 [7] compare the storage technologies using the following 12 characteristics: (1) Energy density, (2) Power density, (3) Storage duration, (4) Range of nominal power of installations, (5) Self-discharge per day, (6) Capital cost, (7) Technical efficiency over a charge-discharge cycle, (8) Lifetime, (9) Maximum number of cycles, (10) Discharge time, (11) Effect on environment, (12) Maturity of technology (Tables 6, 7 and Fig. 5). We summarize their analysis in the appendix and use it to assess the adequacy between the characteristics of the different storage technologies and the problems encountered on island power systems with a high penetration of intermittent renewable power sources (Table 1).

The new Pump Hydro Storage (PHS) devices appropriately respond to most the desired requirements in an island power system.[6] The PHS technology is mature, has been widely implemented in power systems for a long time, and is already used for balancing island power systems. Nevertheless the integration of intermittent renewable energy sources requires the creation of more hydroelectric dams, and the large water reservoirs associated with this technique raise substantial environmental issues. In addition, the local topography does not always allow the creation of new PHS volumes. Consequently, pumped hydro storage will have an important role to play for the island power systems developing intermittent renewable generation in adapted locations. This is already the case for some island power systems as in the Canary Islands (e.g. Gran Canaria or El Hierro [6]) or some Greek islands (see, for instance [34]).

The Compressed Air Energy Storage (CAES) solution is technology under development that has not yet reached commercial maturity. It also requires considerable volumes of air for implementation,[7] which is not easily compatible with the geographical constraints of island power systems.

The electrochemical storage devices (i.e. the battery, flow battery and fuel cell solutions) are the technologies best suited to the need of island power systems with growing integration of intermittent renewable energy in the absence of hydraulic resources. The power electronics required for the insertion of these DC facilities on the AC island power systems solves the problems of power quality (variation in voltage magnitude, transient voltages and currents, harmonic content in the waveforms). Their temporal dynamics are relevant to their participation in the system balancing. Moreover, the storage duration of these technologies is around one or two days and consequently aligned with the needs of island power systems. Finally, the energy and power densities of electrochemical storage devices are adapted to space constraints in the island power systems. This offers considerable flexibility in the location of electrochemical storage devices, an advantage that facilitates the resolution of congestion. The major drawback of all existing electrochemical storage technologies is their cost. However, Baker [4] explains that current electrochemical technologies can expect to see substantial technological improvements in the next 30 to 40 years. By improving various components of the battery (electrodes, current

[5] The conclusion may be a little bit different for the continental power system because the best location for storage devices should then be at the substation between the low voltage and medium voltage networks [9].

[6] For the most standard types of PHS, these storage devices cannot deal alone with the problems of harmonics. However, it is possible to complete these installations in a relatively inexpensive manner to solve this problem. Besides, a new type of PHS with variable speed includes power electronics and is consequently able to deal with the problem of power quality.

[7] On the continent, this is not necessarily a problem because the CAES can be installed underground using natural sealed cavities.

Table 2
Suitability of storage technologies to the needs of power systems with increasing integration of intermittent renewable generation.

Power system needs with increasing integration of intermittent renewable generation	Technologies					
	PHS	CAES	Fuel cells	Batteries	Flow batteries	Others*
Power quality from power electronics	New → Yes Old → No	No	Yes	Yes	Yes	Yes
Balancing	Yes	Yes	Yes	Yes	Yes	Reserves only
At least daily storage duration	Yes	Yes	Yes	Yes	Yes	Yes
Location flexibility	No	No	Yes	Yes	Partly	Yes

* (SMES, flywheel, supercapacity).

collectors, membranes, electrolytes, packaging cells, etc.) it is possible to increase the energy density of electrochemical storage devices by 10 to 20%, increase their lifetime (in years and number of cycles) and, of course, reduce their manufacturing costs. Nevertheless, these different electrochemical storage technologies clearly have not the same potential development in island power systems.

The different battery technologies do not offer the same benefits. The lead-acid batteries have a medium lifetime that is poorly compatible with a storage device that is expected to operate for several years. Despite its advanced technological maturity, the environmental and health impact of lead represents a major disadvantage for these batteries. Although Nickel–Cadmium (Ni–Cd) batteries have better technical features in terms of robustness over time, they pose similar environmental and health problems owing to the presence of cadmium. The last three types of batteries (NaS, ZEBRA and Li-ion) have a smaller impact on the environment (because of the low presence of heavy metals). Moreover, their stage of development is close to commercial maturity. Their robustness over time is also relatively good. The ZEBRA battery is distinguished by its low cost. The Li-ion battery has the advantage of being more efficient in the duration of a charge–discharge cycle. The Lithium-ion technology with a size of few kWs could be installed in homes to ease self-consumption when they already have a photovoltaic system.[8] The Lithium-ion solution can also reach the size of hundreds of kWs. The NaS battery is rated suitable for larger installations of a few megawatts.

Storage using fuel cells has one major drawback, however, due to its low efficiency. In addition, fuel cells technologies are still in their development phase and consequently suffer from a crippling problem of maturity for rapid deployment.

Flow batteries have low energy density. The size of these facilities would reduce the number of options for their location. And such technologies are still at a stage of development too far from the commercial level for easy and robust deployment.

The last storage technologies (SMES for Superconducting Magnetic Energy Storage, Flywheel and supercapacity) are mainly storage systems designed to deliver power as and when needed (for the extremely rapid storage and release of energy) that would not solve the problem of balancing generation and power system load within a 1-day horizon.

Table 2 summarizes the benefits provided by the different storage technologies to the power system.

To conclude, our analysis of support mechanisms for storage devices on island power systems focuses principally on the electrochemical storage devices (fuel cells, batteries and flow batteries).

[8] This battery technology is intended for use in electric vehicles. Thus, subject to adequate communication infrastructures, the batteries of these vehicles might be involved in balancing the system provided they are connected to the network.

3. What forms of public support for storage devices?

Electrochemical storage devices are being developed from a technical perspective but have not yet reached the commercial maturity required to allow development beyond their role as a support mechanism. For the efficient development of all these technologies, it is therefore necessary to adapt the support to the level of maturity of these technologies. At the same time, the gains offered by the storage of electricity are maximized if the facilities inject and withdraw electricity at the best moment and if the storage facilities are appropriately located on the grid. Such efficient management of storage is easily achieved in a refined market design. However, not all electrical systems necessarily possess a design of this kind. This is especially true for the island power systems in Europe.

Therefore, we first recall the theory of public support for the development of renewable innovation. Second, we establish the support mechanisms to be implemented in a perfect market design. Finally, we study how these support mechanisms must be adapted in the case of a market design whose features are misaligned with the ideal scenario.

3.1. Public support for the development of renewable innovation

To identify the public support scheme best-suited to each development stage of an environmental innovation, we refer to a simplified version of the linear model of innovation. There are multiple ways to understand and forecast the possible forms taken by the different stages of innovation and the factors determining the success and failure of innovation as it proceed towards commercial release. In this paper we have chosen to explore this question thanks to the simplest model of innovation diffusion following an S curve, as in Foxon et al. [14]. Further studies may be needed in the future to take account of other forms of innovation diffusion such as disruptive innovations [8] or even the "no diffusion" case in the presence of path dependency issues [23,24,16,10,15].

In our view and following Foxon et al. [14], the S curve diffusion model can be divided into 5 stages: 1° invention, 2° the applied R&D phase, 3° the demonstration phase, 4° the pre-commercial release and the 5° the commercial release [12]. In this representation, the diffusion of technology follows 3 phases, an initial one with the take-off of technology (stages 1 & 2), a second one with the acceleration of development under the effect of increasing returns from adoption and cost reductions (stages 3 & 4) and a third one with the slowdown of development when the technology approaches commercial maturity (stages 4 & 5). For an efficient support of technological innovations, the support schemes must be adapted to each of these stages.[9] Fig. 4 borrowed from Foxon et al.

[9] In this paper, we do no challenge this model but rather use it to identify the adaptation needed by the public policies.

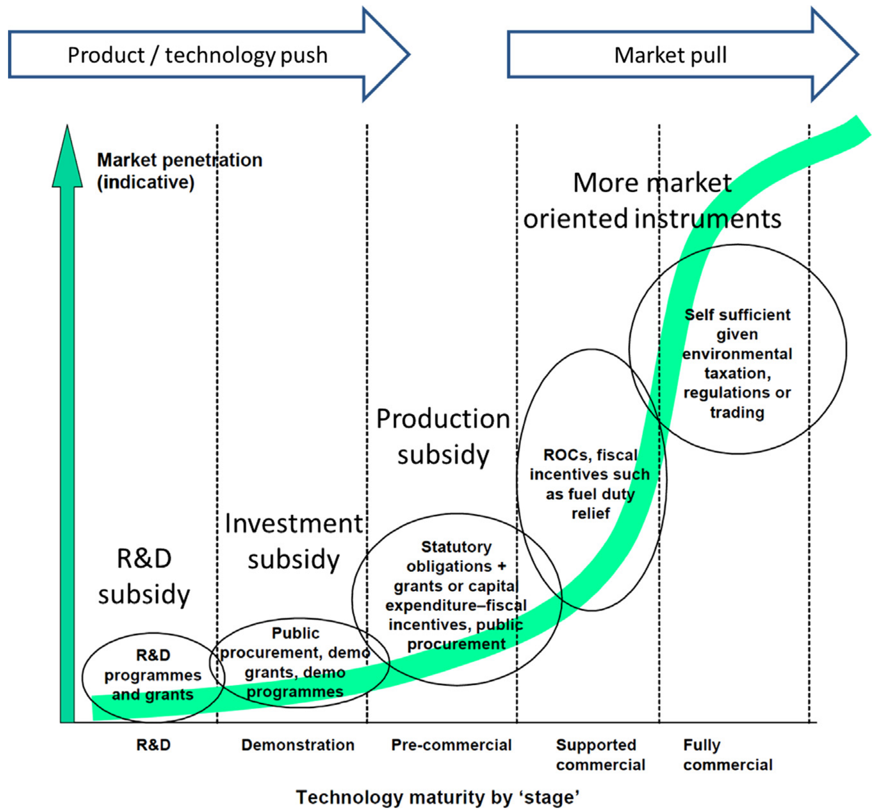

Fig. 4. The typical pattern for the adequacy between the types of support schemes for RES and the level of maturity (from [14,12]).

[14] provides a summary of the tools that can be implemented at each stage in the development of innovative technology. We will now describe the different stages in innovative technology and the support tools best suited to them.

The first phase is RD&D. It focuses on the development of new scientific and technological knowledge. Public laboratories and government subsidies are involved at this stage, possibly under public-private partnerships.

The demonstration phase is characterized by the realization of a few prototype units of increasing size to attain a commercial size. The demonstration phase is marked by the construction of a niche market through large subsidies granted to users to allow innovators to develop manufacturing processes for industrial-size units. This phase is financed by grants for investment, especially when the technologies (for RES) are capital intensive. This phase makes it possible to create a market in which small businesses can develop their capacities.

The pre-deployment phase is the stage characterized by the effects of learning by doing and by using and when the production of the technology can be scaled up. This period is dominated by the development of industrial expertise and dissemination. It is accompanied by the adjustment of institutional rules to facilitate the diffusion of technology and to create a large-scale market for this technology. Bigger players come to support smaller innovators. Without adequate support, investments made by manufacturers as well as those made by users may involve considerable risk at this point.

Two approaches are possible to support innovative technology at this stage. Either an investment subsidy is directly granted to the users of the technology or the investors are paid a production subsidy through a feed-in tariff that guarantees the revenue of their new equipment during a large part of their lifetime (commonly 15 to 20 years). The choice between investment subsidy and production subsidy at this stage depends on the characteristics of the cost of innovative technology, the financial size of adopters, the level of maturity of the technology and regulatory opportunism.[10]

The investment subsidy is adapted to early pre-commercial deployment when the cost structure of technology is dominated by upfront capital costs. It can take different forms: direct subsidies, loan subsidies, tax credits, etc. The investment subsidy exhibits three weaknesses in the prematurity phase. First, this support is exposed to the political risk of a stop-and-go policy because related subsidies are directly paid by the State. Second, the investment subsidy does not encourage users to seek the most efficient equipment, a tendency that fails to ensure the rapid selection of the most reliable manufacturers. Third, it also fails to provide incentives for the maintenance of equipment and can lead to the equipment being stopped at the first major challenge when it is already depreciated.

The production subsidy becomes a more efficient tool at the pre-commercial maturity stage because it is based on the production performance of installed units. It therefore encourages a search for good performance because the investor receives a payment for the lifetime of the RES investment directly linked to its production. It also encourages the operator to perform needed maintenance to maintain the performance of the facility. The grant

[10] Regulatory opportunism is a crucial point coupled with a feed-in tariff [13]. The extensive literature in regulatory economics shows that having a "credible commitment" of government over time requires both investment safeguards for investors [40] and room for system adaptation by governments [18]. Managing this arbitrage process is important because if the tariff is badly calibrated and becomes too generous (or not generous enough…) for the investors, public action will be needed to provide the necessary correction of errors. Meanwhile, too much public intervention and renegotiation of past agreements should also be avoided because it generates uncertainty for investors [17]. For an extensive survey of these questions see Perez [32] & MacIntyre [26].

Table 3
Extract from the table "Market design, market signals related risks" Hiroux and Saguan [22].

	Potential market signals	Potential integration costs reductions	Market design options		Accuracy of market signals	Risk induced by market signals
Day-ahead and intraday markets	Temporal differentiation of electricity	Balancing and reliability costs	Degree of centralization	Decentralized	0	0
				Centralized	+	−
			Gate closure	Far real-time	0	0
				Close real-time	+	−
Balancing market	Value of electricity at delivery / Value of flexibility	Balancing and reliability costs	Imbalance price	Dual price	0	0
				Single price	+	+
Congestions (and losses) pricing	Locational / temporal differentiation	Congestion and reinforcement costs	Zonal aggregation	Redispatching	0	0
				Zonal	+	+
				Nodal	++	++
Connection and network tariffs	Locational/ temporal differentiation and cost recovery	Congestion and reinforcement costs	Connection and network tariff	Shallow	0	0
				Deep	+	++
				Zonal tariff	++	+

is provided on each device over a period sufficiently long to allow for a normal return on investment. It gradually changes with the reduction of costs thanks to learning effects and is phased out thereafter.

The penultimate phase of technological maturity is the last stage when technology is supported. In this last support phase, the innovative technologies are more exposed to market risk through the support mechanisms. It is thus possible to introduce quota systems (such as green certificates). But the quota systems induce considerable risks and offer limited visibility to investors regarding the return on their investment. Instead, the mechanisms of environmental premium (or feed-in premium that varies with the market prices to ensure a minimum purchase price) offer greater certainty for investors while exposing technological innovations to market risk in a measured manner.[11] Besides, phasing out the level of the environmental premium is a way to integrate progressively the technology as a fully market-friendly solution.

3.2. A support mechanism for storage with a textbook market design

Hiroux and Saguan [22] address the question of a textbook market design for large-scale integration of wind power in Europe. We will use their pioneering work to review the design of a perfect market and to propose support mechanisms for the electrochemical storage in this perfect framework.

Hiroux and Saguan [22] show that it is possible to support massive wind generation while exposing it to the market price in order to have this technology integrated in an efficient, market-friendly way. More specifically, the integration of wind energy is all the more effective (in terms of social surplus for the electrical system) when it corresponds to a perfect market design. Table 3 below reviews all the main options for designing an electricity market and assesses their efficiency. In short, a perfect market design would be as follows: it would be centralized with a gate closure near to real time. The daily intraday and real-time prices would vary with the location of the electrical nodes. A single price would be used for the settlement of real time imbalances.[12] And the network access fees would be zonal. The producer or storage operator receives all the market signals that effectively incentivise him to respect his contractual position in real time, to be constrained on or off when the system needs it and to locate efficiently. Any deviation from this market design would reduce efficiency. These possible deviations are: the decentralization of market design, a gate closure far from real time, a dual pricing for positive and negative imbalances in real time, congestion management with zonal pricing and redispatching, a shallow or deep cost allocation of network costs.

Hiroux and Saguan [22] then show that a feed-in premium that completes typical market revenue (from selling energy and ancillary services) offers a good compromise between exposure to market signals and the need for a minimum amount of financial certainty required for the massive integration of wind power. Of course, some features of the perfect market design lead to an increased risk for market players and, in particular, for clean technologies. This may discourage the adoption of these technologies as long as the support mechanism has not been defined to compensate for this increased risk. Thus, technologies or investors who behave 'best' with respect to these risks will be rewarded. Furthermore, a feed-in premium that completes the market signals is a solution that facilitates the future discontinuation of the support mechanism, gradually reducing the level of this premium. The design of a support mechanism should then take account of revenues provided by market design and the level of maturity of the technology supported.

Applying this framework to electrochemical storage has different implications depending on the maturity of technologies. Fuel cells are still in the technical development stage [7]. Following the Foxon et al. [14] framework, this technology should primarily benefit from public subsidies enabling it to increase its level of RD&D. The exposure of this technology to market signals at this stage of maturity is of no interest.[13]

Flow battery technologies are in the early phase of pre-commercial development [7]. Following the Foxon et al. [14] framework, the support that best suits their level of maturity is an investment grant.[14] At the same time, exposing the technology to market revenue can now make it possible to integrate the needs of the system in the architecture of this storage device. It is then possible to see the investment subsidy as a hedging contract with guaranteed income for the investor. As a consequence, the investor

[11] See Finon and Perez [13] for a comparison of these ways to promote RES technologies for electricity and Perez & Ramos-Real [31] for a Spanish case study.

[12] This is the real-time physical positions with respect to the contractual positions resulting from the market outcomes.

[13] In the case of the hydrogen fuel cell, a niche market can begin to develop [7]. Note that the PHS technology is mature and no support mechanism consequently seems justified in this regard. Some obligations of storability for intermittent RES production might be enough to encourage the development of this technology.

[14] Note that CAES technology presents a similar level of technological maturity [7]. The same rationale could then be applied to designing an adapted support mechanism.

Table 4
Support schemes for electrochemical storage devices in a perfect market design.

Technologies	Technological maturity	Support scheme → associated with the support scheme of intermittent renewable generation
Fuel cells	Developing +	RD&D grant
Flow batteries	Developed −	Investment grant as a hedging contract that completes market revenues
Batteries	Developed +	Feed-in premium with floor that completes market revenues Obtained from tender in a first phase

Table 5
Support schemes for electrochemical storage devices in the French island power system.

Technologies	Technological maturity	Support scheme → associated to the support scheme of intermittent renewable generation
Fuel cells	Developing +	RD&D grant
Flow batteries	Developed −	Investment grant related to the efficient use of the storage facility
Batteries	Developed +	Feed-in tariff with time differentiation Obtained from tender in a first phase

would be initially paid by the market (or the system operator for ancillary services) for all the services provided to the system. This revenue offers an inflow of cash that is all the more rapid as the investor effectively participates in the market. And the government grant would complement this income to reach the specified level of revenue in the contract subsidy.

Battery technologies are at the end of their pre-commercial development phase [7]. They are indeed the most suitable technologies to solve problems by the middle of the decade in some European island systems. The sodium-sulphur (NaS) technology is perfectly suited to the needs of large installations in terms of power (several megawatts). The Li-ion technology is perfectly suited to the power needs of small installations, a photovoltaic installation at home for example.

Following the Foxon et al. [14] framework, the most appropriate support for the pre-commercial level of maturity is a production subsidy. Exposing battery technologies to market revenue can allow them to immediately start integrating the needs of the system in the architecture of the storage devices. It would thus be wise to use a feed-in premium that completes market revenue when the storage facility injects energy into the system.[15]

Meanwhile, these facilities are still scarce. And this is a major difficulty because the regulator has very little knowledge about the cost of these facilities and few options to discover relevant information. Because of this asymmetry of information, we recommend using a tender mechanism in the first phase of support for electrochemical storage devices, where the storage operators propose an injection and withdrawal tariff in their offers. The feed-in premium would then be calculated by the regulator on the basis of this information revealed about the revenues asked by storage operators and the level of market prices (or of regulated prices) in the system in question.

Table 4 summarizes the support mechanism to be associated with each electrochemical storage device in a perfect market design.

3.3. *Support for storage in real market designs: the case of the French island power system*

The study of support for storage technologies in a system with a perfect market design provides a framework for the study of support in any market design. We rely on this preliminary study to recommend support for storage in European island power systems, with a particular focus on the case of France. We make this choice because the market design for the French island power system is very different from the perfect market design[16] and it is well documented and information is easily available. First, we describe the market design of these power systems. Then, we propose a support mechanism adapted to this design.

It is clear that the market design of the French island power systems is very different from the perfect market design.[17] EDF is a vertically integrated utility company, operating a significant proportion of French power plants and ensuring the transmission and distribution of electricity. Third-party access to these networks is regulated. The connection tariff is a deep cost one[18] for the low voltage network,[19] an average deep cost[20] one for medium voltage (for facilities for up to 12 MW) and deep cost for installations in high voltage.[21] In addition, a network access fee applies to producers (mainly for the management and billing in medium voltage and also for the injection in high voltage) but also for consumers. No forward market or centralized real-time is established in these islands. Producers other than EDF connected to island power systems are usually renewable energy producers benefiting from a feed-in tariff.

The market design of the French island power systems raises problems for the integration of storage facilities. The lack of any organized power market in particular makes it impossible to benefit from the gains offered by storage for the entire system. Indeed, a significant proportion of revenue from storage comes from the possibility of inter-temporal trade-offs (withdrawing energy from the system for a time and storing this energy in order to remove it and subsequently inject it back into the system). However, these trade-offs can only be made in the light of power market price signals. Moreover no short run locational signal can

[15] The storage operator would pay the market price to withdraw energy from the system and to store it.

[16] We must take into account the cost of the change in market design to assess the absolute distance between the current market design and the perfect market design.

[17] Source: sei.edf.fr

[18] With a deep cost tariff, the full costs of all new infrastructures required for changes in network utilization (whatever reason: a local increase in consumption, a new connection, increased generating capacity of an existing power plant) will be directly charged to the network users responsible for this change in network use.

[19] The voltage on the low voltage network is less than 1 kV. The voltage of a medium voltage network is between 1 and 50 kV and the voltage of a high voltage network is between 50 and 130 kV.

[20] For connection in medium voltage, a price reduction (*taux de réfaction tarifaire*) is applied. This rate reduction is 40%. When the generator connects to the network, it then pays only 40% of deep cost.

[21] These connection rules are implemented in Metropolitan France for this voltage level. The rule applied in Metropolitan France is the shallow cost tariff. But considering that there is only one high voltage level (63 kV) in the French island power networks, a deep cost tariff is, in fact, applied.

Table 6
Ranges of the characteristics of storage technologies.

Range for the energy density (Wh/Kg)	Range for the power density (W/kg)	Range for the storage duration	Range for the power range for the installations	Range for the self-discharge per day	Range for the capital cost (€/kW)	Range for the efficiency of a charge-discharge cycle	Range for the lifetime (years)	Range for the possible number of cycles	Range for the discharge time	Range for the effect on environment	Range for the technological maturity
Very low (0.01 < X < 10)	Very low (10 < X < 25)	Very weak (from seconds to minutes)	Very weak (0 < X < 50 kW)	Very weak (X < 0.1%)	Weak (100 < X < 600)	Weak (X < 60%)	Very weak (X < 1)	Very weak (X < 100)	Very weak (from milliseconds to seconds),	None	Mature
Low (10 < X < 30)	Low (25 < X < 50)	Weak (from seconds to hours)	Weak (50 kW < X < 500 kW)	Weak (0.1% < X < 1%)	Medium (600 < X < 1500)	Medium (60% < X < 90%)	Weak (1 < X < 50)	Weak (100 < X < 500)	Weak (from seconds to minutes)	Weak (few wastes)	Developed +
Medium (30 < X < 50)	Medium (50 < X < 150)	Medium (from minutes to hours),	Medium (500 kW < X < 50 MW)	Medium (1% < X < 10%)	High (X > 1500)	High (X > 90%)	Medium (5 < X < 15)	Medium (500 < X < 1500)	Medium (from seconds to hours)	Important (toxic wastes to deal with, possible recycling)	Developed –
High (50 < X < 150)	High (150 < X < 1000)	Long (from minutes to days)	High (50 MW < X < 300 MW)	High (10% < X < 30%)			High (15 < X < 50)	High (1500 < X- < 20,000)	High (from minutes to hours)	Negative (CO2 emissions or destroyed trees – from hydro dams)	Developing +
Very high (X > 150)	Very high (X > 1000)	Very long (from hours to months)	Very high (X > 300 MW)	Very high (X > 30%)			Very high (X > 50)	Very high (X > 20 000)	Very high (from hours to days)		Developing-

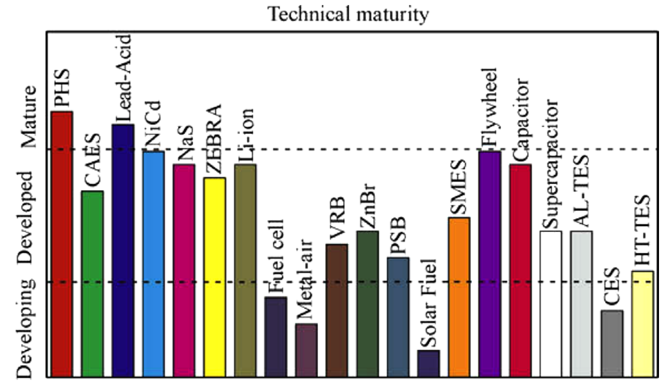

Fig. 5. Technical maturity of the different storage technologies from Chen et al. [7].

be provided.[22] This problem is only partly solved when EDF SEI publishes the accommodation capacity of the island network substations.

More importantly, storage facilities face a major problem in the French island power systems (and more widely in Metropolitan France): they must pay the network access fee both as producers and as consumers. This measure is known to impact significantly the profitability of the storage facilities in France [20]. It is important to note that in the absence of precise locational signals in the design of the French island power system, it appears easier to associate systematically the support for a storage device with intermittent renewable generation.[23] Given the considered market design we described, the three support mechanisms previously proposed with a perfect market design are modified as follow. First, the support for fuel cells is related to RD&D grants and the establishment of a niche market so it is not affected by market design considerations in the island power systems.

Second, for the flow batteries, in the absence of market prices, the investment subsidy for the appropriate level of maturity of this technology is applied in its simplest form. To give the investor an incentive to use this storage device efficiently, it is possible to link this investment subsidy with the performance of the facility. This principle was applied to subsidies given to the photovoltaic sector in California [12]. This framework could be adapted in the case of storage. We can then compensate the absence of time-varying power prices defining several time ranges (late night, day and early night, for instance). The performance of the storage facility would consequently be calculated on the basis of the periods mainly used to store and remove energy. Such a mechanism would push the storage device to store more late at night (when the conventional thermal power plants are reluctant to drop their production below the technical limits) and during the day (in bright sunlight) to remove energy at peak time in early night.

Lastly, without market prices and given their pre-commercial level of maturity, battery technologies should be supported with a feed-in tariff. Nevertheless, to ensure energy is stored and removed more efficiently, these rates should be differentiated in time as we described earlier for the flow batteries. The regulator will then have to set the feed-in tariff according to the

[22] The deep cost access fee does not provide a locational signal because no signal is publicly available. The generator must ask to connect to know the connection cost.

[23] As mentioned previously, the conclusion is a little bit different in continental Europe because the need for storage related to the massive integration of intermittent renewable generation is more located at the substation between the low and medium voltage networks.

Table 7
Evaluation of the different storage technologies.

	Energy density (Wh/Kg)	Power density (W/Kg)	Storage duration	Nominal power	Self-discharge / day	Capital cost (€/KW)*	Efficicency of a charge cycle (%)	Lifetime (years)	Number of cycles	Discharge time	Effect environment	Technological maturity
Pump Hydro Storage	Very weak	Sans objet	Very long	Very High	Very weak	High	Medium	Very high	Very high	Very high	Negative	Mature
CAES	Medium	Sans objet	Very long	High	Weak	Medium	Medium	High	Very high	Very high	Negative	Developped +
Batteries												
Lead-acid	Medium	High	Long	Medium	Weak	Weak	Medium	Medium	Medium	Medium	Negative	Mature
NiCd	High	High	Long	Medium	Weak	Medium	Medium	High	High	Medium	Negative	Developped +
NaS	High	High	Short	Medium	High	High	Medium	Medium	High	Medium	Important	Developped +
ZEBRA	High	High	Short	Weak	High	Weak	Medium	Medium	High	Medium	Important	Developped +
Li-ion	High	High	Long	Weak	Weak	High	High	Medium	High	High	Important	Developped +
Fuel cell												
Generic fuel cell	Very High	Very High	Very long	Medium	Very weak	High	Weak	Medium	Medium	High	Important	Developing +
Metal Air	Very High	Weak	Very long	Very weak	Very weak	Weak	Weak	Medium	Weak	High	Weak	Developing -
Flow Battery	No			No								
VRB	Weak	Medium	Very long	Medium	Weak	Medium	Medium	Medium	High	Medium	Important	Developped -
ZnBr	Medium	High	Very long	Medium	Weak	High	Medium	Medium	High	Medium	Important	Developped -
PSB	Weak	High	Very long	Medium	Weak	High	Medium	Medium	High	Medium	Important	Developped -
Others												
SMES	Very weak	Very High	Medium	Medium	High	Weak	High	High	Very high	Very short	Important	Developped -
Flying wheel	Weak	Very High	Very Short	Weak	Very high	Weak	High	Medium	Very high	Short	None	Developped +
Supercapacities	Very weak	Very High	Short	Very weak	Very high	Weak	Medium	Very high	Very high	Very short	Weak	Developped +

information about the level of technological maturity he is able to obtain from other stakeholders, by consulting them for instance.[24]

Table 5 summarizes the support mechanism to be associated with each electrochemical storage device in the case of France.

4. Conclusion

The present paper seeks to develop a support mechanism for electricity storage technologies in the European island power systems taking the French island power system as a case study. In order to do so, the paper relies on the linear model of innovation development. The paper expanded on this model using the maturity level of the storage facilities. However, this investigation is limited to certain categories of storage technology by considering two criteria, 1° the storage technologies that can always be technically developed on island power systems, and 2° the storage facilities that meet the challenges of these systems where intermittent renewable energy is developing very rapidly. These challenges are, notably, the problems of harmonics, balancing, and the limitation of curtailment of intermittent renewable generation when network constraints appear.

In a perfect market, it is concluded that the following support scheme should be implemented: (a) an RD&D grant for fuel cells, (b) an investment subsidy designed as a contract hedging device to complete the market and system revenues for the flow battery technologies and (c) an environmental feed-in premium in addition to the market price for the battery technologies. The perfect market provides a lot of information for an efficient location on the network. As a consequence, it is not necessary to link the support of the storage facilities to the support of renewable energy (although *a priori* the storage units will be localized close to these production sources).

Within one European island power market that is very different from the perfect market design, namely the French island power systems, the following has been proposed: (a) an RD&D grant for fuel cells (as previously), (b) a subsidy for investment (possibly in the form of a performance contract) for the flow battery technologies and (c) a feed-in tariff with different prices depending on the time of day for the battery technologies. With no locational signals, it is necessary to combine storage facility support with renewable energy support to be sure the storage unit is located as close as possible to the sources of intermittency for the power system.

The short-run constraints on the French island power systems force us to focus on battery technologies. Moreover, if the support of the storage industry also contributes to the establishment of an innovative European industry, certain technologies in particular should be promoted. SAFT in France, Evonik or Litec in Germany are flagship of their national industries, and their battery product lines mainly focus on lithium-ion- and nickel-based technologies. It is pointless for these firms to try to catch up on the NaS technology given the leadership of NGK in this area ([12] for a similar analysis in the case of PV). It is then necessary to design the support mechanism and to determine the level of subsidy to encourage the storage technologies developed by these firms.

Of course, the present work calls for additional work in other isolated islands, where market designs can be very different from the one we have analyzed here. In a broader perspective, the role of

[24] Here the quality of regulatory intervention is crucial. If the regulatory action leads to a renegotiation of previously signed contracts, the effect for future investments will be determined by the assessment of the investors. If they collectively feel that the regulator is right in his action towards past, badly crafted contracts, the investment climate will be reinforced. On the contrary, if they collectively think that the regulator behaves in an inappropriate manner, investors will quit the market for more reliable environments.

storage and the efficient way to support it should also be analyzed in larger interconnected systems. Finally and more generally, the links between innovation and regulatory decisions in electricity systems are still poorly studied and require further research.

Appendix

To make easier the reading of the analysis by Chen et al. [7], we placed each technology in a range as defined in Table 6 that corresponds to each of the following characteristics: (1) Energy density, (2) Power density, (3) Storage duration, (4) Range of nominal power of installations, (5) (Self-discharge per day, (6) Capital cost, (7) Technical efficiency over a charge-discharge cycle, (8) Lifetime, (9) Maximum number of cycles, (10) Discharge time, (11) Effect on environment, (12) Maturity of technology. Chen et al. [7]. propose the graph below (Fig. 5) to detail the maturity of the different storage technologies. To be coherent with the 5 stages of the linear model of innovation that we present in Section 2 of the paper, we define 5 categories of technological maturity. All in all, we sum up these different categories in Table 7.

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